Elemental composition of ambient fine particles in urban schools: sources of children's exposure

Leigh R. Crilley[A], Godwin A. Ayoko[A*], Eduard Stelcer[B], David D. Cohen[B], Mandana Mazaheri[A] and Lidia Morawska[A]

[A] International Laboratory for Air Quality and Health, Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, QLD, 4001, Australia.

[B] Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW 2232, Australia.

*Corresponding author: g.ayoko@qut.edu.au

Abstract

Currently, there is a limited understanding of the sources of ambient fine particles that contribute to the exposure of children at urban schools. Since the size and chemical composition of airborne particle are key parameters for determining the source as well as toxicity, PM_1 particles (mass concentration of particles with an aerodynamic diameter less than 1 µm) were collected at 24 urban schools in Brisbane, Australia and their elemental composition determined. Based on the elemental composition four main sources were identified; secondary sulphates, biomass burning, vehicle and industrial emissions. The largest contributing source was industrial emissions and this was considered as the main source of trace elements in the PM_1 that children were exposed to at school. PM_1 concentrations at the schools were compared to the elemental composition of the $PM_{2.5}$ particles (mass concentration of particles with an aerodynamic diameter less than 2.5 µm) from a previous study conducted at a suburban and roadside site in Brisbane. This comparison revealed that the more toxic heavy metals (V, Cr, Ni, Cu, Zn and Pb), mostly from vehicle and industrial emissions, were predominantly in the PM_1 fraction. Thus, the results from this study points to PM_1 as a potentially better particle size fraction for investigating the health effects of airborne particles.

Keywords

Exposure at schools, industrial emissions, PM_1 composition, health effects,

1.0 Introduction

Long-term exposure to airborne particles in adults has been associated with a number of harmful effects to cardiovascular (Brook et al., 2010) and respiratory systems (Pope et al., 2002). Due to their immature immune systems and faster breathing rates, children are more susceptible to these detrimental health effects (Rückerl et al., 2011; Zhang and Zhu, 2010). In an urban environment vehicle emissions are one of the main sources of airborne particles (Morawska et al., 2008) and children's exposure to vehicle emissions has therefore been associated with a number of long-term negative health effects, including increased wheezing (Ryan et al., 2009) and the development of asthma (Gehring et al., 2010).

The size and chemical composition of ambient particles are important parameters in determining their toxicity (Heal et al., 2012). A clear relationship has been established between exposure to $PM_{2.5}$ (mass concentration of particles with an aerodynamic diameter less than 2.5 µm) and adverse cardiovascular effects (Brook et al., 2010) and increased levels of lung cancer (Pope et al., 2002). Thus many epidemiological studies have focused on $PM_{2.5}$ when investigating the health effects of air pollution (Heal et al., 2012). The chemical composition of airborne particles is also thought to affect the toxicity as it contains toxic and carcinogenic compounds, such as polycyclic aromatic hydrocarbons and heavy metals (Harrison et al., 2004). In urban environments it has been observed that the majority of the toxic metals, such as V, Ni, Cu, As, Cd and Pb are in the PM_1 fraction (Cheng et al., 2009; Moreno et al., 2011).

Trace metals can be used as surrogates for determining the influences of various sources (such as traffic, industrial and ship emissions), to the overall composition of the airborne particles (Arhami et al., 2009; Moreno et al., 2006). Children spend a large portion of their day at school and traffic emissions have been shown to be a prominent source at schools in

urban areas, primarily due to the influence of school buses (Hochstetler et al., 2011). However, not all schools are serviced by school buses. Instead, many schools are more influenced by local and school-related traffic (such as drop-off and pick up times) or other urban sources nearby. Therefore, the relative contribution of different sources at urban schools may differ from other urban environments. Overall, to date, there is limited information on the contributing sources of ambient fine particles that children are exposed to at urban schools (Mejía et al., 2011).

The current study aimed to address the aforementioned gaps in knowledge in the sources of trace elements that contribute to children's exposure at schools by analysing the elemental composition of PM_1 samples obtained from various schools. To determine the size fraction of the detected elements, particularly the heavy metals, concentrations from the present study were compared to previous work on $PM_{2.5}$ composition in Brisbane. The sources of the trace elements that children were exposed to at schools, with a focus on toxic heavy metals, were identified using principal component analysis (PCA). In addition, we sought to determine the more relevant size fraction (PM_1 versus $PM_{2.5}$) for exposure assessment based upon their elemental composition.

2.0 Method

2.1 Sampling Sites and Instrumentation

The PM_1 sampling was conducted from October 2010 till August 2012 as part of a larger project known as UPTECH (www.ilaqh.qut.edu.au/Misc/UPTECH%20Home.htm) which was designed to study the effect of ultrafine particles from traffic emissions on children's health. 25 randomly selected schools within the Brisbane Metropolitan Area participated in this study and are referred to as S01 to S25. At each school a centrally located site, which was assumed to give the best overall exposure, was chosen to conduct the measurements. Inlets for the sampling were placed approximately 3m off the ground and on the top of a monitoring trailer, which served to house a TSI DustTrak DRX (model 8534) and a Monitor Sensors

µSmart Series weather station. The DustTrak DRX is an optical instrument that simultaneously measures the mass concentration of ambient particles across the PM_1, $PM_{2.5}$, PM_{10} and total PM fractions. Optically measured particle mass concentrations are not equivalent to gravimetric results however they are useful in this study to examine the relative contributions of PM_1 to $PM_{2.5}$ concentrations. Particle mass concentrations for each of these size fractions were recorded and averaged every 30s by the DustTrak DRX.

Data from nearby weather stations was also obtained from the Bureau of Meteorology (BOM) and Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) as the collected data at some of the schools would have been affected by local winds due to schools buildings. Traffic counts were taken on the busiest road in the school's proximity, referred to as the main road throughout. In the traffic count, cars, motorbikes and scooters were classified as light-duty vehicles. Light trucks with 2, 3 and 4 axels were classified as medium vehicle and long articulated trucks classified as heavy vehicles.

2.2 Sampling Methodology

The PM_1 particles were collected on 47 mm, 0.2 µm pore size Teflon filters (Whatman) with the filter area reduced to 25 mm to concentrate the particles, using cyclone type sampler with a flow rate of 16.7 litres per minute (lpm), maintained with critical orifices. For each sampling period two filters were collected with the flow rate split across the filters at 5.8 lpm. The sampling period was 24 hours, from 08:00 until 08:00 the next day, Monday to Friday for one week to give a total of four samples at each school. No PM_1 samples were collected at S11 due to instrument malfunction. This sampling regime typically gave sampling volumes of 8.2 m^3. After sampling, each filter was placed in a Petri dish and then sealed in a ziplock bag. Gravimetric analysis of filters was performed pre and post sample collection, as well as blanks, on a 5 point Mettler Toledo micro balance in the Chemistry laboratories at Queensland University of Technology. Prior to weighing, all filters were preconditioned at a constant temperature and humidity (25°C and 40%) for at least 24 hours.

2.3 Elemental Analysis

Elemental analysis was performed using ion beam analysis at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia on a STAR accelerator (2.0-MV HVEE tandetron, High Voltage Engineering Europa, Amersfoort, The Netherlands) (Cohen et al., 2010) using particle induced gamma emissions (PIGE) spectroscopy and particle induced x-ray emission (PIXE) spectroscopy. These techniques can measure the following commonly occurring elements in PM_1 particles: Na, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Sr, Cd and Pb and have been described in details elsewhere (Cohen, 1998; Cohen et al., 1996; Cohen et al., 2004). Na was analysed by PIGE and the remaining 20 elements by PIXE.

2.4 Quality Control

Flow rate for the PM_1 cyclone: this was checked at the beginning of each sample and always set to within ±0.1 lpm of the desired flow rate.

Gravimetric analysis: a test filter that was given the same preconditioning treatment as the sample filters, was weighed repeatedly over the project. The standard deviation of the mean weight was 10 µg, indicating high stability of the balance.

Ion beam analysis: The average minimum detection limit (MDL) ranged from 3.3 to 40.8 ng m^{-3} as summarised in Table S1 (Supporting Information) for the PIXE elements. For Na, the PIGE analysis program could not calculate a MDL, as Na was not detected in any samples. However, previous work by Friend et al. (2011) found an average MDL of 35.5 and a range of 20 to 60 ng m^{-3} for $PM_{2.5}$ sampled in Brisbane.

2.5 Data Analysis

Principal component analysis (PCA) and ANOVA were performed using SPSS v19. For the PCA, missing values were replaced by the mean and Varimax rotation was applied to the

loadings. Only factors that had an eigenvalue above one were considered. Rose plots of wind direction and speed were calculated using IGOR Pro v6.22.

3.0 Results and Discussion

3.1 Meteorological characteristics during sampling

The project was conducted over nearly two years with sampling covering all of the seasons, as reflected in the range of meteorological conditions recorded at the schools and are listed in Table 1. Brisbane is a subtropical city with a low level of variation between the average daily temperatures and an average temperature ranging from 13 to 24°C across all the schools (Table 1). May until October is the cooler, drier period with generally more stable weather and is referred to as winter. November to April is the summer and it is warmer, with higher humidity and rainfall. These weather conditions were observed throughout the project, as shown in Table 1. Wind rose plots were used to determine the wind direction during the sampling period, and these are given in the Supporting Information Figure S1 and summarised in Table 1.

Table 1

3.2 Traffic characteristics of the schools

The majority of the schools were all in residential areas and had mostly light vehicles passing the schools, though schools such as S04, S06, S08, S23 and S25 were beside roads that service industrial/commercial areas and had higher levels of medium and heavy vehicles. Some schools such as S07, S09, S19 and S20 were located on busy arterial roads and others such as S01, S16 and S18 were beside quiet residential streets, as indicated by the traffic volume passing the schools.

3.3 Gravimetric analysis

The average mass of PM_1 measured on the filters across the 24 schools was 90 ± 60 µg and this equated to an average concentration of 11 ± 7 µg m^{-3}. Though the DustTrak is an optical

instrument and thus the concentrations are not directly comparable to the gravimetric results, the ratios of PM_1 to $PM_{2.5}$ are expected to be the same for DustTrak and gravimetric analysis. On average, the PM_1 made up 83 ± 17% of the $PM_{2.5}$ fraction by mass, as determined by the DustTrak. Therefore the PM_1 fraction made up the majority of the $PM_{2.5}$ that children were exposed to at the schools.

3.4 Average elemental composition

The average concentrations and summary statistics for each element across all of the schools are presented in Table 2. The most abundant element at the schools was generally S. The largest source of S in Brisbane is secondary sulphates (Friend et al., 2011). The next most abundant elements on average from Table 2 were Si, Ca and Fe, which along with the other elements known to be of a crustal origin such as K, Mn and Ti (Friend et al., 2011; Radhi et al., 2011) made a significant component of the total trace element concentration of the PM_1 at the schools. Brisbane is a coastal city; therefore Cl was abundant at the schools, which was likely due to the influence of sea salt particles. However, Na was below the detection limit for all samples possibly due in part to the higher MDL of PIGE technique compared to PIXE (Cohen, 1998) and this is discussed further in Section 3.7. The remaining elements, P, V, Cr, Co, Cu, Zn, Br, Cd and Pb, are related to anthropogenic sources, such as vehicle, ship and industrial emissions (Friend et al., 2011; Moreno et al., 2006) and the contributing sources are investigated further in Section 3.6.

Table 2

3.5 School-based PM_1 elemental composition

The concentrations of the elements were compared between the schools in order to investigate the driving factors of the concentrations of heavy metals that children are exposed to at school. The average PM_1 concentration of selected elements (S, V, Fe, Ni, Zn and Pb) are given in Figure 1, with that of Si, Cr, Cu and Br given in Figure S2 (Supporting Information). From Figure 1, except for Fe and Zn, S02 clearly had the relatively highest

concentrations of all of these elements and this was likely due to the combined influence of two sources: industrial/shipping and traffic emissions. Along with the six elements from Figure 1, S02 also had elevated concentrations of elements such as Cr, Cu and Br (Figure S2) compared to the other 23 schools. The predominant wind direction at S02 was from the east (Table 1) and both the Port of Brisbane (approximately 10 km) and the main road (which recorded comparatively high traffic counts) lie in this direction. It is noteworthy that elements with elevated concentrations at S02 have previously been associated with industrial (Moreno et al., 2006), shipping (Arhami et al., 2009), and traffic emissions (Lough et al., 2005; Thorpe and Harrison, 2008).

Figure 1

S02, S04 and S17 are within similar distance to the port and during sampling the main wind direction was from the port area. These three schools recorded comparatively high concentrations of S and V (Figure 1), elements previously associated with shipping emissions (Arhami et al., 2009), which suggests emissions from the port affected the schools. Also from Figure 1, the schools that recorded some of the highest concentrations of Fe, Zn and Pb (S02, S10, S19 and S20) were schools beside some of the more heavily trafficked roads (Table 1) implicating traffic emissions (Lough et al., 2005; Thorpe and Harrison, 2008). However S07 and S09 had equally high traffic counts and yet recorded relatively low concentrations of these elements, which was likely due to the fact that the main wind direction was not from the main road at these schools (Table 1).

3.6 Source Identification across Brisbane Metropolitan Area using PCA

Overall, the PM1 elemental concentrations at the schools indicate an array of contributing sources to the elemental composition, especially for the anthropogenic elements at the schools. Therefore PCA was applied to the average PM_1 elemental concentrations of the detected elements at each school in order to determine the contributing sources and their relative importance. With all of the schools included, the number of components identified

was only three and all of the elements except for Al, Fe and Zn have high loadings in the first component (See Table S3, Supporting Information). These three elements were the only elements that were not elevated at S02 compared to the rest of the schools (Figures 1 and S2), and this shows that S02 was an outlier. Therefore PCA was applied to the data without S02 and the number of components increased to seven, explaining a total of 81% of the variance, with the results shown in Table 3 along with the proposed source identity for each component.

Table 3

From Table 3 most of the sources of the PM_1 at the schools identified were anthropogenic. Component 1 was characterised by highest loadings of S and also high loadings of Si, P, Cl and Ca and was attributed to secondary sulphates (Friend et al., 2011). This component explained the most variance and was thus a significant source of the PM_1. Two oil refineries present in Brisbane emit a combined $6.7x10^6$ kg of SO_2 into the atmosphere per annum (NPI, 2013) and are thus contributing to the high concentrations of secondary sulphates in Brisbane.

A vehicle emission source was identified in the PCA, which was characterised by Ti, Mn, Br and Pb (Component 2); these elements have been associated with vehicle emissions (Lin et al., 2005) and references therein). Though leaded petrol was banned in 2002 in Queensland, Pb and Br are still associated with vehicle emissions in Brisbane (Friend et al., 2011) and in other studies around the world (Lin et al., 2005; Lough et al., 2005). Furthermore, the ratio of the average Pb and Br concentrations at the schools was about 2 (Table 2), which is characteristic of vehicle emissions (Cohen, 1998). In addition, Mn and Ti have also previously been associated vehicle exhaust emissions (Wang et al., 2003) and this suggests that the source of the component is vehicle exhaust emissions. This component accounted for the second highest amount of variance and this evidence point to vehicle emissions as a second most important anthropogenic source at the schools.

Component 3 was attributed primarily to ship emissions due to the high loadings of Ni and V, which have been previously associated with oil combustion/shipping emissions (Arhami et al., 2009). Cr and Sr also recorded high loadings in component 3 and have previously been associated with petrochemical (Singh et al., 2002) and cement works (Widory et al., 2010), industries that are present around the Port of Brisbane.

Along with high loadings of Fe and Zn, K had the highest loading in component 4. As K is a well-known tracer for biomass burning (See e.g. (Richard et al., 2011), component 4 was attributed to biomass burning. Zn and Fe have also previously been found in the emissions from biomass combustion (Friend et al., 2011) and as elements in the PM_1 fraction are generally related more to combustion processes than to crustal material or vehicle wear emissions (Minguillón et al., 2012), this observation further point to biomass burning as the source.

Components 5 to 7 were also attributed to emissions from industry. Pollution from industrial activities can be highly specific chemically (Moreno et al., 2006) and this explains why a number of components related to industrial sources are observed in the PCA results. Cd and Sr recorded high loadings in component 5 while component 7 was characterised by high loadings of Co; all of these elements have been previously shown to be from industrial sources (Moreno et al., 2006; Widory et al., 2010). Co in particular has been previously been attributed to industrial sources in Brisbane (Lim et al., 2005). The main industrial areas of Brisbane are in the southwest and northeast parts and the major wind direction at schools that recorded high concentrations of Co and Cd (S03, S05, S20 and S23) was from these areas (Figure S1). The short sampling times at each school made identifying individual industrial sources difficult, however likely industrial sources include various metallurgical and cement plants (Moreno et al., 2006; Widory et al., 2010), all of which are present in Brisbane.

Copper, the characteristic element of component 6, has been proposed as a tracer for brake wear emissions (Thorpe and Harrison, 2008); however the lack of other metals with high loadings, such as Fe, which are also known to be from brake wear (Gietl et al., 2010) suggests that the source may not be related to vehicle movement. In addition, brake wear particles are expected to be in the larger size fractions (Iijima et al., 2007) while emissions from anthropogenic combustion processes, as opposed to mechanical processes, are found more in smaller sizes (Minguillón et al., 2012). Therefore the source of the Cu in the PM_1 was assigned to industrial emissions, which has been observed before for fine particles in Brisbane (Lim et al., 2005) and elsewhere (Moreno et al., 2006; Viana et al., 2008). All of the industrial sources (Components 3, 5-7) combined explained more variance that the vehicle emissions component, indicating that industrial emissions were the largest anthropogenic source of metals in the PM_1 fraction in Brisbane. Thus industrial emissions were the main anthropogenic source of elements in the PM_1 that children were exposed to at schools.

3.7 Comparison to a previous Brisbane study

In Table 4, the PM_1 element concentrations from the schools were compared to a similar study by Friend et al. (2011) on the $PM_{2.5}$ composition at a suburban and roadside site in Brisbane. The sampling by Friend et al. (2011) encompassed three years and one year of sampling for the suburban and roadside site, respectively. Therefore they are considered to be representative of the typical ambient concentrations for these types of sites in Brisbane.

Sodium was detected in the previous study (Table 4), as sea salt particles are generally in the coarse mode; however in the present study the sampled particles were in the PM_1 faction. Combined with the higher detection limit for Na outlined in previous sections, it is therefore not surprising that the amounts of Na in the samples were not detectable.

Table 4

Crustal elements (Al, Si, K, Ti and Fe) had lower concentrations in the PM_1 fraction compared to the $PM_{2.5}$ (Table 4). One-way ANOVA analysis of these concentrations found

that compared to the $PM_{2.5}$ concentrations at the suburban site (Friend et al., 2011), Al, Si, Ti and Fe had statistically significant lower concentrations at the schools. Crustal elements are generally found preferentially in the larger size fractions and this would explain the lower concentrations observed at the schools (Minguillón et al., 2012; Richard et al., 2011). The smaller size fraction collected at the schools, combined with the Fe rich nature of Australian soils (Radhi et al., 2011) would partly explain why Al was not detected in every sample at the schools (Table 2).

On average, the concentrations of P, Cr, Ni, Br and Pb in the PM_1 at the schools were found to be 2-3 times higher than those found at the roadside and suburban sites (Table 4) (Friend et al., 2011). Vehicle emissions are one of the primary sources of Ni, Br and Pb in urban environments (Moreno et al., 2006) and thus the higher concentrations at the schools points to a contribution from school-related traffic. However, analysis by ANOVA found that none of the higher average concentrations at the schools compared to the other sites were statistically significant ($p>0.05$).

That the PM_1 concentrations of V, Cr, Ni, Cu, Br and Pb in the current work were similar to the suburban and roadside $PM_{2.5}$ concentrations (Table 4), suggests that these elements were predominantly in the PM_1 fraction. Richard et al. (2011) showed that the $PM_{1\text{-}2.5}$ fraction is the crossover between the coarse crustal material and particles associated with anthropogenic sources, in agreement with the results from this study.

3.8 Implications for investigating health effects of airborne particles

In the current study, measurements with a DustTrak determined that the majority of the $PM_{2.5}$ (82%) by mass, was actually in the PM_1 fraction where the more toxic heavy metals (e.g. V, Ni, Zn and Pb (Chen and Lippmann, 2009) were preferentially found. Thus based on the size and chemical composition, the PM_1 fraction may have greater detrimental health effects compared to $PM_{2.5}$. Currently the main metric for measuring the concentration of airborne particles is $PM_{2.5}$ in many epidemiological studies, as clear relationships have been

established between $PM_{2.5}$ and harmful health effects (See e.g. (Brook et al., 2010). However, the results from this study suggest that the more appropriate size fraction to use when investigating the health effects of airborne particles would be PM_1.

4.0 Conclusions

The trace elemental composition of the PM_1 was analysed at 24 urban schools to determine the sources of airborne particles that children are exposed to at urban schools. The elemental composition varied from school to school as a result of differing source contributions. PCA was applied to identify these sources within Brisbane and found four types of emission sources: secondary sulphates, biomass burning, vehicle and industrial. The four sources classed as industrial were distinguished by different elements, notably a shipping/port emission source with high loadings of V, Cr, Ni and Sr. Combined, industrial emissions, rather than vehicle emissions were the largest anthropogenic source of trace elements in the PM_1 that children were exposed to at school.

Comparison of the elemental concentrations from this study to previous work on the $PM_{2.5}$ elemental composition studies conducted in Brisbane (Friend et al., 2011) revealed that the contribution of Pb, Br and Ni had concentrations 2-3 times higher at the schools, pointing to an influence from school related traffic. However, analysis by ANOVA revealed that this difference was not statistically significant and generally elements from anthropogenic sources had similar concentrations. Therefore the anthropogenic elements, which are generally more toxic (e.g. V, Ni, Zn and Pb), were predominantly in the PM_1. As the smaller particles are thought to have a greater detrimental health effect, the results from this study point to PM_1 being a potentially better metric to use when investigating the health effects of airborne particles. Further work is required to confirm this hypothesis.

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Table 1: Average traffic and meteorological conditions at the schools during the sampling.

School	Date	Temp. (°C)	RH (%)	Wind speed (m s^{-1})	Prominent wind direction	Frequency of wind from main road (%)	Direction of main road	Local traffic (veh h^{-1})	% Light	% Med	% Heavy
S01	Nov-10	23	65	4.90	East	16	South	158	95.6	3.8	0.6
S02	Oct-10	22	76	3.31	East	35	East	859	95.2	4.6	0.3
S03	Nov-10	23	71	2.81	Northeast	0	Southwest	312	98.3	1.6	0.1
S04	Mar-11	23	60	1.63	East	5	West	806	87.0	7.9	2.2
S05	Mar-11	22	80	1.22	South	26	South	616	96.5	3.0	0.4
S06	May-11	15	73	3.78	West	2	East	268	87.8	8.2	2.9
S07	Jun-11	17	65	0.72	South	0	Northeast	1019	95.3	3.5	0.6
S08	Jun-11	13	69	1.11	West	19	Northwest	565	86.0	13.4	0.7
S09	Jul-11	13	65	1.91	W/SW	0	North	1164	90.7	3.6	1.8
S10	Aug-11	14	73	2.1	South	7	West	893	95.1	3.3	0.7
S12	Aug-11	15	75	0.75	West	2	South	176	97.3	2.5	0.2
S13	Oct-11	21	66	1.31	South	4	West	655	95.6	3.6	0.5
S14	Oct-11	22	74	1.09	Southeast	4	East	173	95.7	3.8	0.5
S15	Nov-11	24	65	4.13	Northeast	12	West	858	92.1	5.9	0.9
S16	Nov-11	25	75	0.96	North	40	North	46	97.8	1.6	0.4
S17	Dec-11	24	71	0.91	Southeast	15	East	757	95.3	3.0	0.6
S18	Mar-12	22	71	1.00	S/SE	0	West	35	97.9	2.1	0
S19	Mar-12	23	79	3.27	South	31	South	1093	89.9	3.2	2.0
S20	Apr-12	20	63	0.68	West	17	East	1121	96.2	2.5	0.8
S21	Jun-12	14	58	0.78	West	31	West	151	97.4	2.1	0.4
S22	Jun-12	14	66	0.64	West	1	Northwest	469	96.8	2.5	0.6
S23	Jul-12	15	60	0.66	South	40	S/SE	657	71.1	28	0.6
S24	Aug-12	15	40	2.99	West	3	North	160	97.1	2.4	0.5
S25	Aug-12	15	68	3.53	North	31	S/SW	332	92.0	6.5	1.2

Table 2: Summary statistics for the PM_1 concentration of the elements at all schools (ng m^{-3}),

	Average	Standard deviation	Min.	Max.	Median	% Detected
Na	0	0.0	0.0	0.0	0.0	0
Al	1.6	6.1	0.0	50.9	0.0	22
Si	75.8	69.2	17.9	401.4	65.7	100
P	6.3	7.1	0.0	45.6	4.4	97
S	177.9	130.1	63.5	760.1	154.1	100
Cl	21.2	28.8	0.0	166.5	11.5	99
K	8.9	9.2	0.0	51.2	6.2	98
Ca	28.9	25.5	5.0	133.9	24.7	100
Ti	2.0	2.2	0.0	13.0	1.4	84
V	0.6	1.4	0.0	10.7	0.0	33
Cr	2.8	7.0	0.0	53.1	1.0	85
Mn	4.4	6.5	0.0	55.8	2.4	97
Fe	19.1	18.3	0.0	83.9	12.4	98
Co	0.3	0.9	0.0	6.5	0.0	22
Ni	0.9	2.9	0.0	25.3	0.2	55
Cu	3.0	6.9	0.0	43.9	1.4	81
Zn	5.9	7.1	0.0	34.0	2.9	90
Br	5.6	11.6	0.0	59.5	2.8	68
Sr	10.3	27.3	0.0	191.1	3.3	61
Cd	5.5	19.1	0.0	123.8	0.0	22
Pb	10.3	27.9	0.0	238.0	3.0	68

Table 3: PCA results for the schools excluding S02.

	Component						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Si	***0.83***	0.31	0.04	0.32	0.12	0.23	-0.04
P	***0.87***	0.18	0.13	-0.26	-0.06	-0.07	-0.08
S	***0.94***	-0.10	-0.02	0.12	-0.17	0.05	0.10
Cl	***0.58***	0.46	0.12	-0.26	0.33	-0.19	0.10
K	0.28	-0.03	-0.04	***0.73***	-0.28	0.07	0.15
Ca	***0.82***	0.20	-0.06	0.37	-0.04	0.21	-0.01
Ti	0.29	***0.85***	0.02	0.09	0.12	-0.06	0.04
Cr	0.25	0.10	***0.87***	0.07	-0.05	-0.10	0.03
Mn	0.24	***0.65***	0.03	0.34	0.48	-0.07	0.09
Fe	-0.27	0.33	0.52	***0.62***	0.16	0.04	-0.20
Ni	-0.12	-0.05	***0.83***	0.10	0.14	-0.02	0.16
Cu	0.22	0.06	-0.02	-0.03	0.05	***0.90***	0.02
Zn	0.07	-0.13	0.31	***0.68***	0.25	-0.11	-0.23
Br	0.31	***0.54***	0.22	-0.23	0.24	-0.40	0.01
Sr	0.13	0.19	***0.60***	0.03	***0.61***	0.14	-0.06
Pb	-0.05	***0.80***	0.14	-0.14	-0.11	0.34	0.01
Al	0.22	-0.09	0.02	-0.08	-0.66	-0.17	0.11
V	-0.03	0.47	***0.62***	0.06	-0.23	0.04	-0.45
Co	0.00	0.08	0.08	-0.05	0.00	0.01	***0.91***
Cd	0.05	0.00	0.06	-0.17	***0.68***	-0.37	0.24
Variance (%)	19.6	14.4	13.3	10.1	10.0	7.3	6.4
Eiginvalue	3.93	2.88	2.67	2.02	1.99	1.46	1.28
Source	**Secondary Sulphate**	**Vehicle emission**	**Ship/ Port**	**Biomass burning**	**Industry**	**Industry**	**Industry**

Table 4: Comparison of the average PM_1 elemental concentrations (ng m^{-3}) at the schools (current study) to $PM_{2.5}$ elemental concentrations (ng m^{-3}) at a suburban and roadside site in Brisbane (Friend et al., 2011).

Site	Suburban		Roadside		Schools	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Na	330.8	237.0	332.1	181.8	0	0
Al	41.6	236.5	104.2	474.6	1.6	6.1
Si	133.4	698.1	324.7	1428.4	75.8	69.2
P	2.9	3.1	1.9	2.1	6.3	7.1
S	282.4	159.4	291.9	156.2	177.9	130.1
Cl	231.5	300.9	246.9	294.0	21.2	28.8
K	54.7	83.9	81.8	177.1	8.9	9.2
Ca	25.0	46.1	50.2	104.0	28.9	25.5
Ti	7.2	39.2	20.7	87.3	2.0	2.2
V	0.8	1.0	1.3	2.3	0.6	1.4
Cr	0.7	1.3	0.8	0.9	2.8	7.0
Mn	5.3	9.4	4.9	14.3	4.4	6.5
Fe	85.4	329.5	241.9	761.2	19.1	18.3
Co	0.7	2.3	1.3	5.2	0.3	0.9
Ni	0.5	0.6	0.4	0.3	0.9	2.9
Cu	2.0	1.9	9.9	7.7	3.0	6.9
Zn	15.5	39.5	14.2	13.1	5.9	7.1
Br	3.0	2.4	3.8	2.2	5.6	11.6
Pb	5.0	4.2	5.6	3.8	10.3	27.9

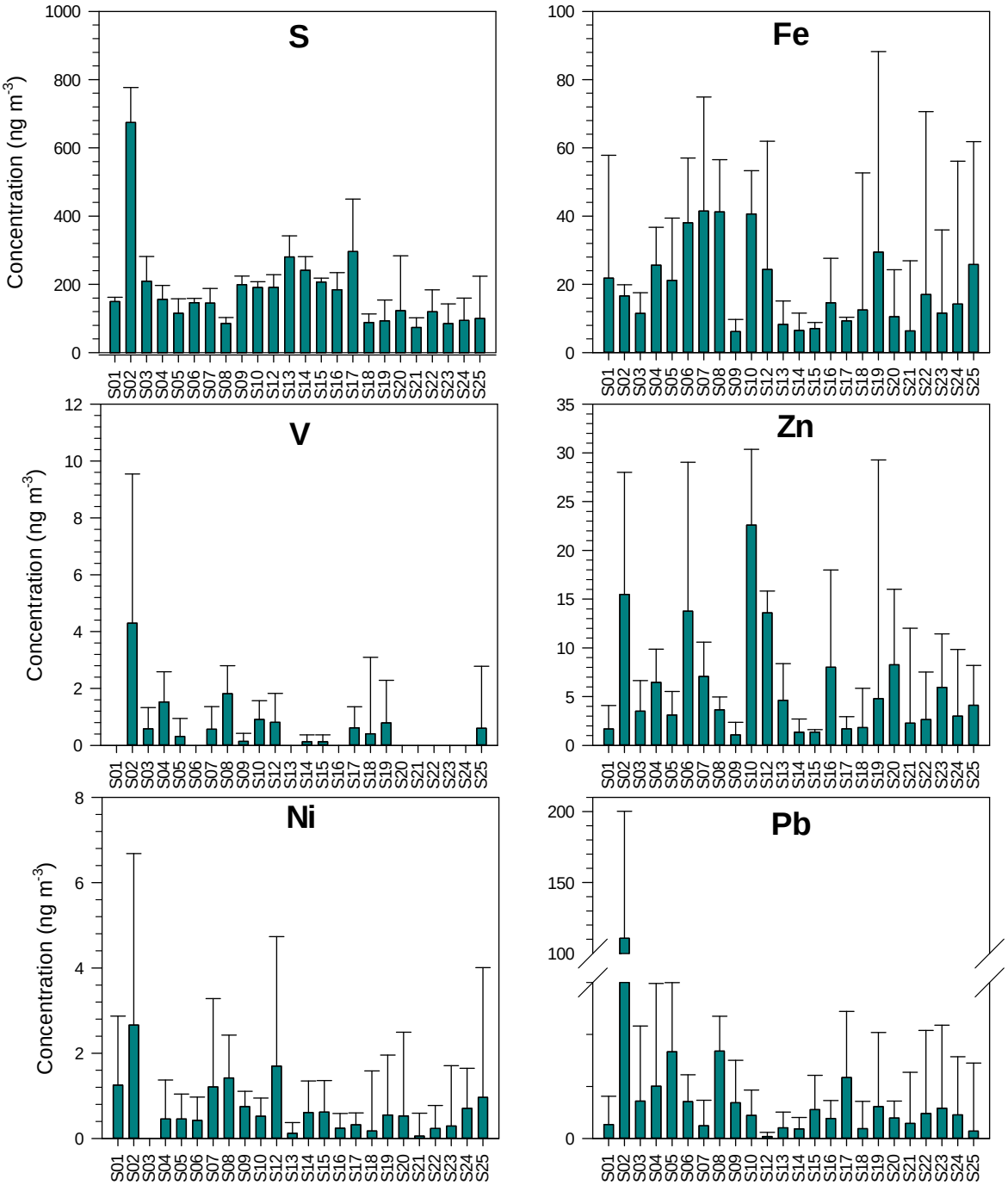

Figure 1: Average PM_1 concentrations at each school for selected elements. Error bars represent 1 standard deviation.

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Supporting Information for:

Elemental composition of ambient fine particles in urban schools: sources of children's exposure

Leigh R. Crilley[A], Godwin A. Ayoko[A], Eduard Stelcer[B], David D. Cohen[B], Mandana Mazaheri[A] and Lidia Morawska[A]

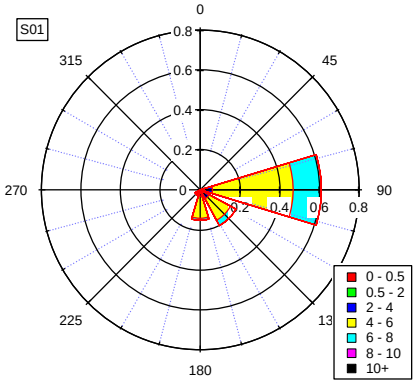
[A] International Laboratory for Air Quality and Health, Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, QLD, 4001, Australia.

[B] Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW, 2232, Australia.

The supporting information contains 2 figures and 2 tables.

Table S1: Summary of the minimum detection limits (MDL) for each element in ng m^{-3}. Note for Na the PIGE analysis program only calculates a MDL when Na is detected.

	Average	Min	Max
Na	0.0	0.0	0.0
Al	18.7	8.1	36.9
Si	11.5	5.1	23.0
P	10.3	4.7	20.6
S	9.6	4.4	19.1
Cl	10.0	4.7	19.7
K	9.1	4.2	17.5
Ca	8.5	3.9	16.3
Ti	6.9	3.0	13.0
V	5.8	2.5	10.7
Cr	4.6	1.9	8.2
Mn	3.8	1.6	6.8
Fe	3.5	1.4	6.5
Co	4.0	1.6	7.8
Ni	3.3	1.4	6.2
Cu	3.5	1.6	6.7
Zn	4.0	1.7	7.7
Br	12.7	5.8	25.5
Sr	32.4	15.2	70.0
Cd	40.8	0.0	648.7
Pb	20.3	9.4	40.7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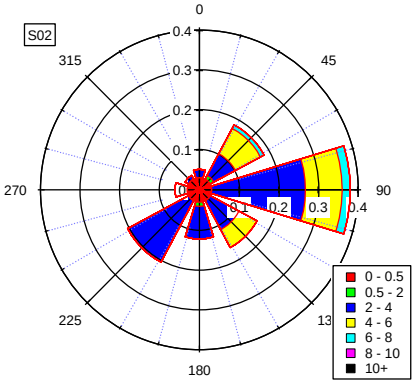
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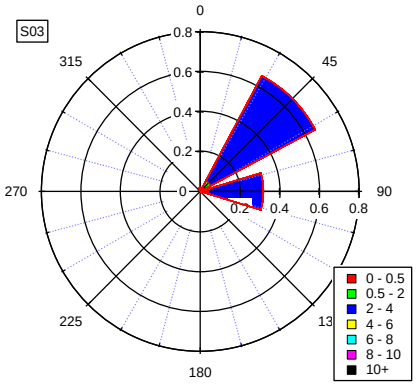
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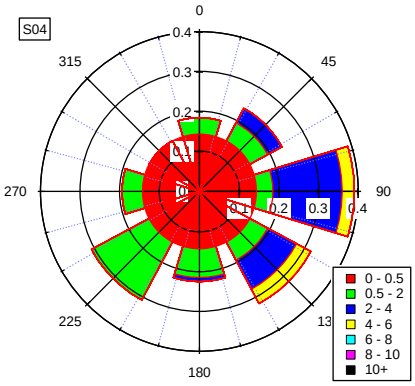
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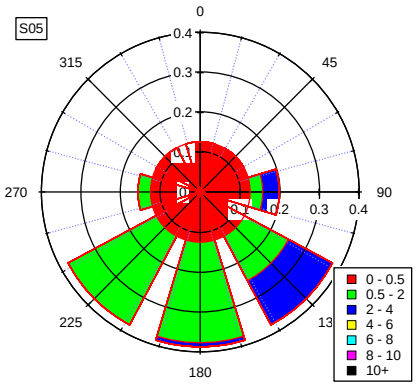
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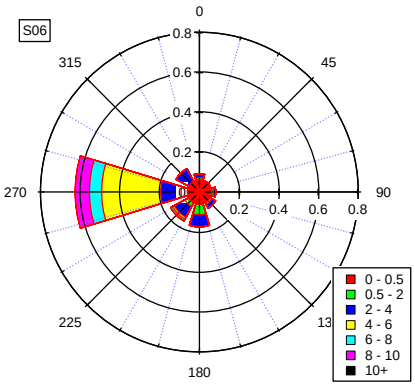
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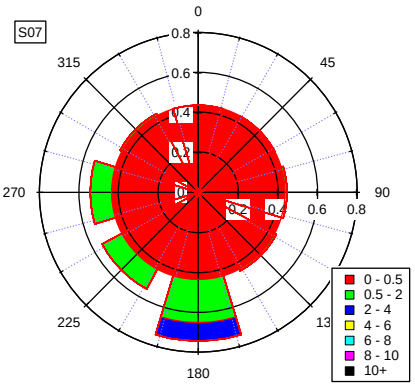
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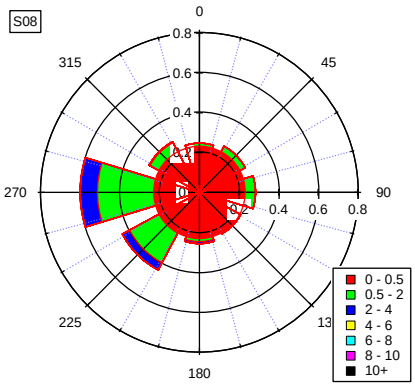
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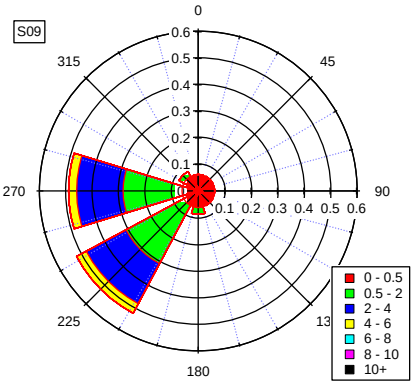
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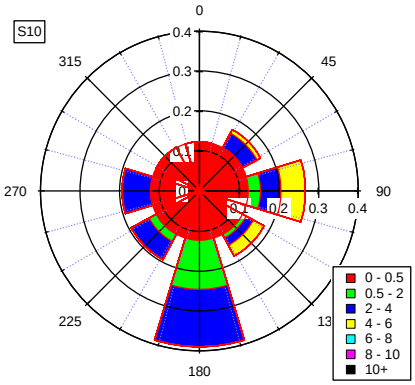
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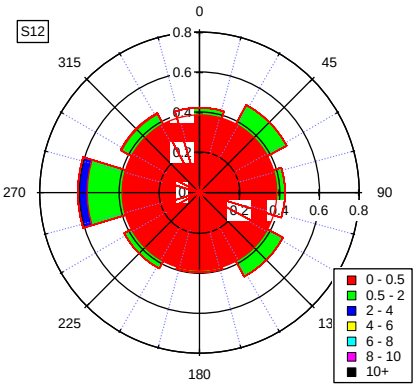
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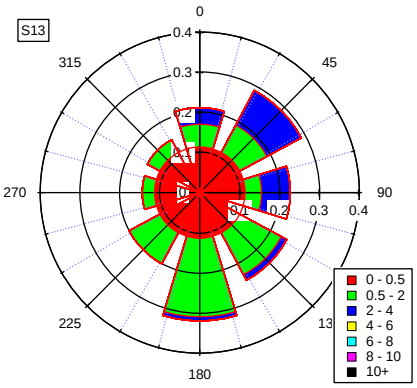
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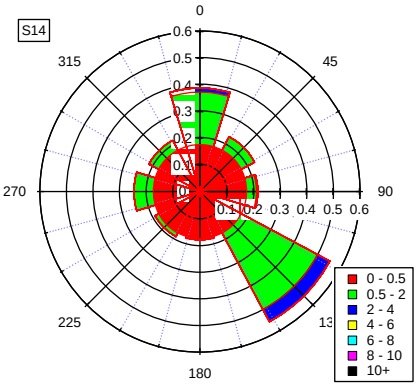
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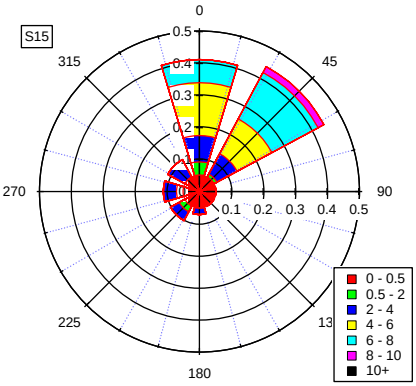
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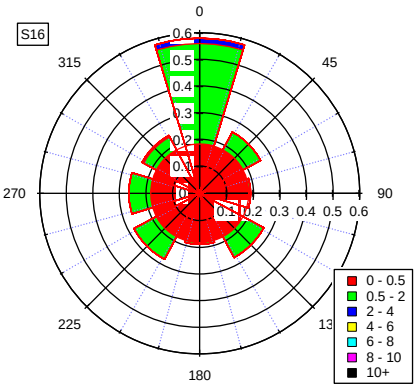
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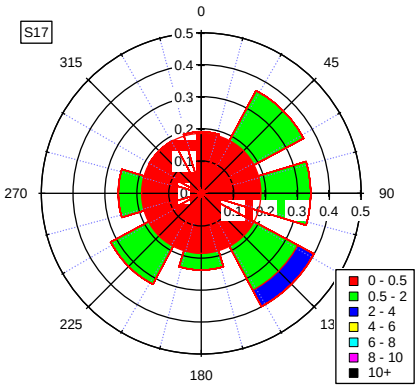
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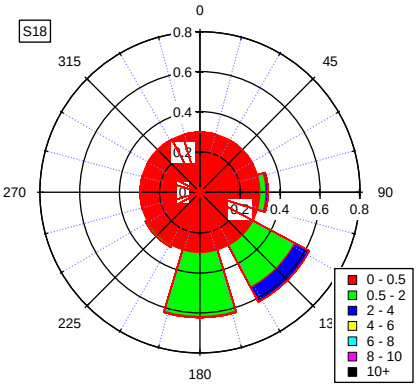
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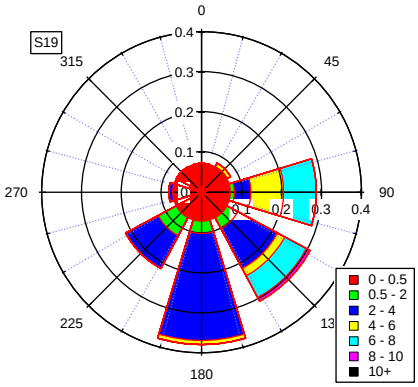
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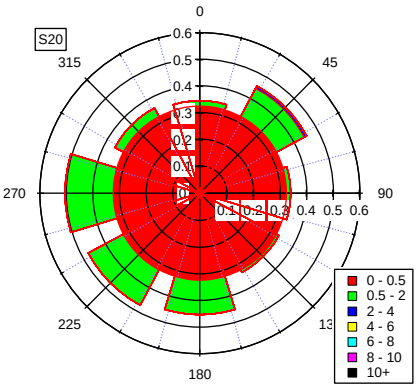
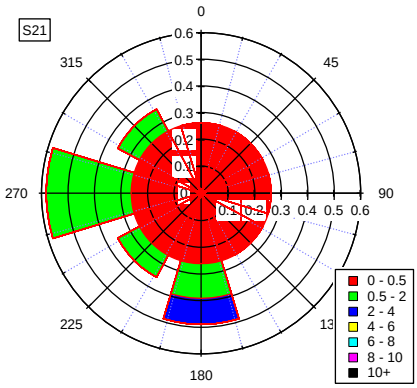

S20
0
45
90
135
180
225
270
315
0.1
0.2
0.3
0.4
0.5
0.6
0 - 0.5
0.5 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10+


S21
0
45
90
135
180
225
270
315
0.1
0.2
0.3
0.4
0.5
0.6
0 - 0.5
0.5 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10+

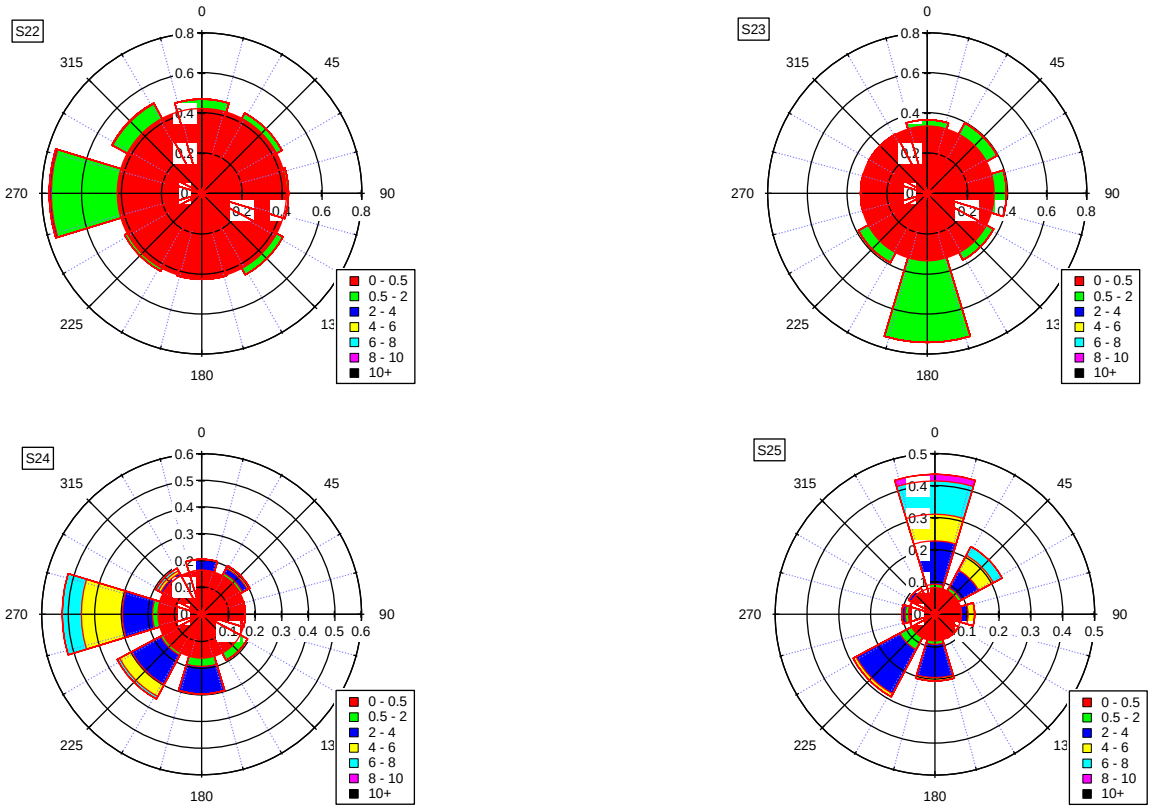


Figure S1: Wind rose plots of the sampling period at each school

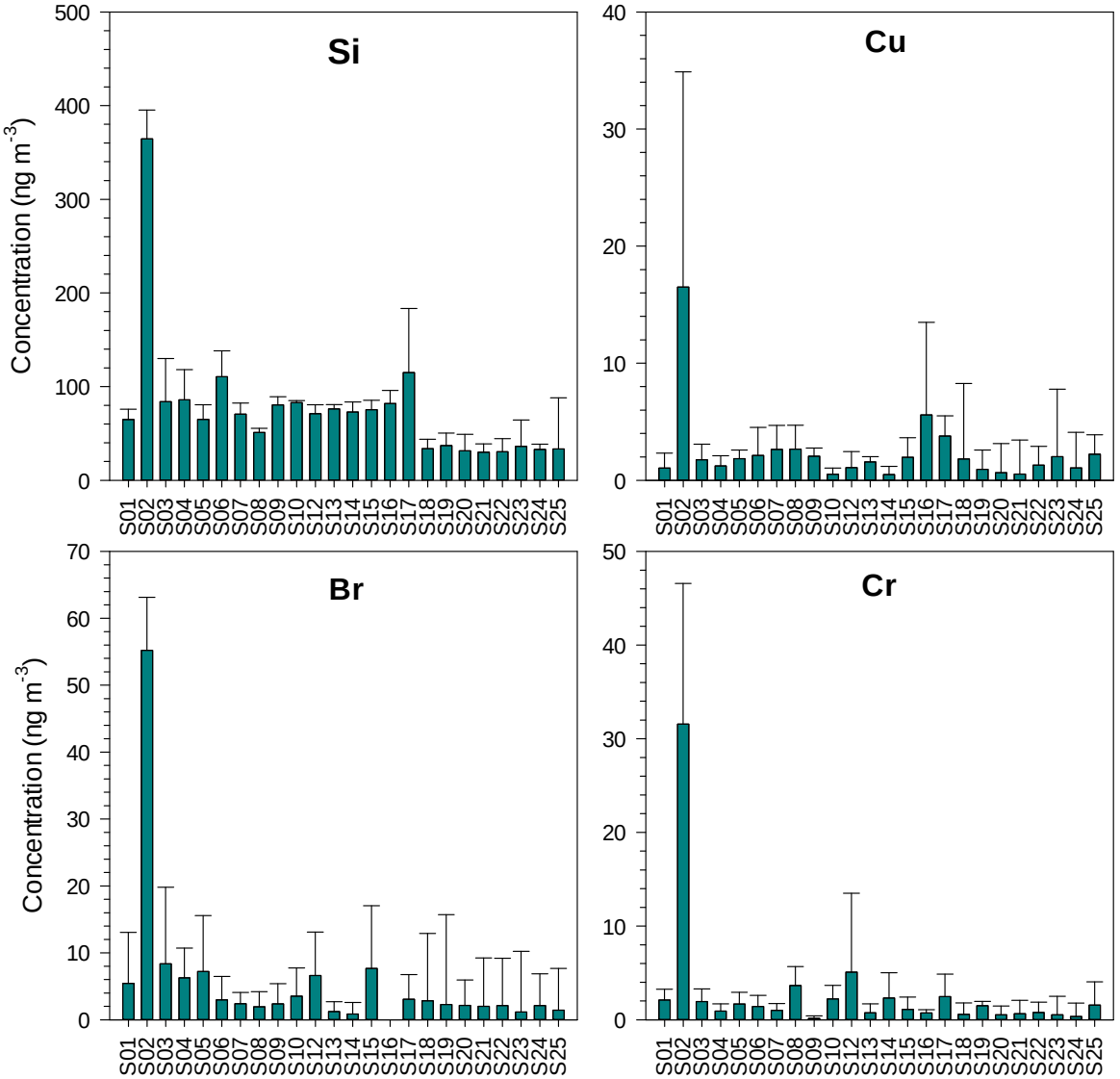


Figure S2: Average PM_1 concentrations of selected elements at all of the schools. Error bars represent 1 standard deviation.

Table S2: Principal Component Analysis for all of the schools.

	Component		
	1	2	3
Al	-0.12	-0.15	***0.80***
Sl	***0.95***	0.19	0.14
P	***0.92***	-0.01	0.17
S	***0.91***	0.05	0.34
Cl	***0.90***	0.01	-0.04
K	0.43	0.46	0.49
Ca	***0.91***	0.19	0.22
Ti	***0.72***	0.19	-0.07
V	***0.82***	0.37	-0.08
Cr	***0.96***	0.19	0.02
Mn	***0.94***	0.23	-0.06
Fe	-0.14	***0.91***	-0.20
Ni	***0.67***	0.40	-0.20
Cu	***0.92***	0.10	0.04
Zn	0.28	***0.77***	0.06
Br	***0.97***	0.11	-0.03
Sr	***0.96***	0.19	-0.06
Pb	***0.96***	0.13	-0.02
Co	***0.85***	0.00	-0.01
Cd	***0.95***	0.10	-0.07
Variance (%)	66.1	77.3	83.3
Eiginvalue	13.22	2.24	1.19